III-Nitride LED Efficiency Droop Models: A Critical Status Review

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Abstract – **GaN- and AlN-based light-emitting diodes (LEDs) suffer from a severe efficiency reduction with increasing injection current (droop). Based on different theoretical models, several physical mechanisms have been proposed to explain the efficiency droop; however, conclusive experimental evidence is still missing for these proposals, and none of them is generally accepted. This presentation reviews and evaluates the main efficiency droop models currently under consideration.**

III-nitride LEDs based on GaN or AlN deliver the desired high efficiency only at relatively low current and at relatively low brightness. At the elevated injection current required in practical high-brightness applications, the internal quantum efficiency (IQE) is substantially reduced. This efficiency droop phenomenon is observed across a broad wavelength spectrum, with and without self-heating. It originates in carrier loss mechanisms which prevent electron-hole pairs from generating photons inside the active layer. Several and partially contradicting proposals have been developed to explain the IQE droop. Among them are density-activated defect recombination (DADR),[1] enhanced Auger recombination,[2] and electron leakage.[3] However, conclusive experimental evidence is still missing and none of these proposals is generally accepted.[4] Figure 1 demonstrates that any of the three main models can be used to reproduce the same efficiency droop characteristic. Recent studies have confirmed that none of the proposed models is able to single-handedly explain the broad variety of efficiency droop observations.[5,6]

The internal quantum efficiency is equal to the fraction of the total current that feeds the radiative recombination inside the active layers. Figure 2 illustrates the different current components. There are only three possible options for injected electrons to avoid photon generation (B) inside the active layer: Shockley-Read-Hall (SRH) recombination inside the active layer (A), Auger recombination inside the active layer (C), or electron leakage into the p-doped side of the LED accompanied by a reduced hole injection into the active layer. Accordingly, there are three main groups of droop models, as given above.

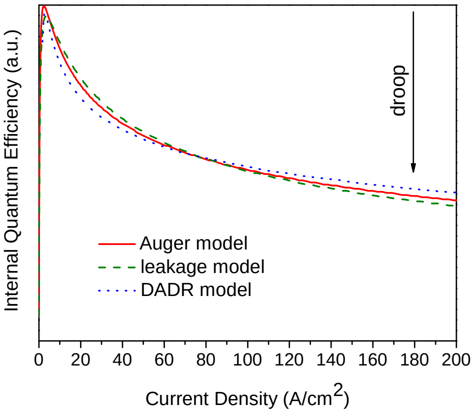

Fig. 1: Efficiency droop characteristics calculated with different models.

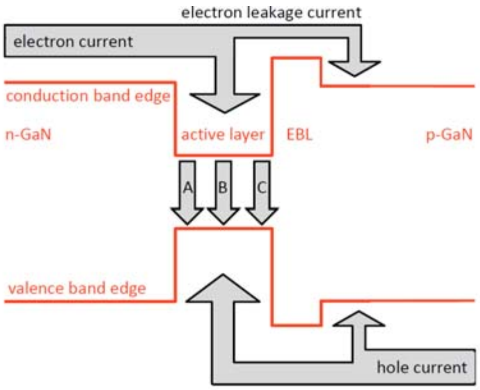

Fig. 2: Schematic LED energy band diagram with illustration of current components (A – Shockley-Read-Hall recombination, B – spontaneous emission, C – Auger recombination, EBL – electron blocking layer).

Most experimental droop investigations apply the so-called ABC model to fit measured IQE characteristics:

$$IQE = B n^2 / (A n + B n^2 + C n^3) \tag{1}$$

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with *n* giving the quantum well (QW) carrier density. The fit parameters A, B, and C are often assumed to represent the processes illustrated in Fig. 2. Such assumption is convenient but it is inappropriate for the following reasons. The possibility of carrier leakage from the QW is neglected. Even with an additional leakage term in (1), the parameter C may also be influenced by leakage.[7] Fundamental models show that simple power-law dependencies for spontaneous emission and Auger recombination break down at elevated carrier densities.[8] All three parameters were demonstrated to depend on the carrier density.[1,9,10] Different ABC parameter sets can lead to the same result.[6] Thus, we here focus on models beyond the simple ABC approach.

The DADR model shows good agreement with IQE measurements at low current densities, and its combination with a carrier localization model[11] also results in good agreement at low temperatures.[6] However, it fails to reproduce the efficiency droop observed at higher current densities.[6] The same is true for a band tail localization model,[12] as well as for a droop model based on the influence of MQW barrier states.[13] Experimentally, carrier localization effects are only observed at very low temperatures.[14]

Auger recombination was proposed as a possible droop mechanism based on a simple ABC fit.[2] But theory predicts a very weak direct Auger process for wide-band-gap materials, and in particular for InGaN/GaN QWs.[15] Thus, indirect Auger recombination was proposed as a possible explanation, mediated by electron-phonon coupling and alloy scattering,[10] but the calculated Auger coefficients are only valid for bulk materials and they are below the values required to fully explain the efficiency droop.[5,6] Reliable calculations for quantum wells are still not available.[16] Recent measurements of hot electron emission are attributed to QW Auger recombination,[17] but these results are still in dispute.

Electron leakage into p-doped layers can be caused by incomplete QW electron capture (hot electrons),[18,19] thermionic emission from the quantum wells,[3] Auger recombination,[20] and by tunneling from the quantum wells.[21] However, the leakage current is very sensitive to the properties of the electron blocking layer (EBL), especially the p-doping.[22] The sensitivity of leakage calculations to other AlGaN EBL parameter variations is illustrated in Fig. 3. The theoretically predicted built-in interface polarization charge density is often arbitrarily reduced in GaN-LED simulations to match measured IQE characteristics.[3] A polarization reduction by factor 0.6 eliminates the electron leakage in Fig. 3 almost completely. The conduction band offset ratio exerts an even stronger influence in Fig. 3, its reduction from 0.6 to 0.5 changes the electron leakage rate from 1.5% to 98%. The insufficient knowledge of these EBL parameters calls almost all of the many published simulation studies on EBL design and optimization into question.[23] Direct measurements of the electron leakage indicate that it is not strong enough to fully account for the efficiency droop.[24]

In conclusion, further improvements and combinations of droop models are needed. More attention should be paid to the validation of material parameters employed in these models to match measured results. However, most importantly, the direct experimental confirmation of proposed droop mechanisms is essential. For instance, electron leakage should be experimentally quantified, e.g., by measuring the photon emission from the p-doped layers,[25] before it is claimed to cause the efficiency droop.

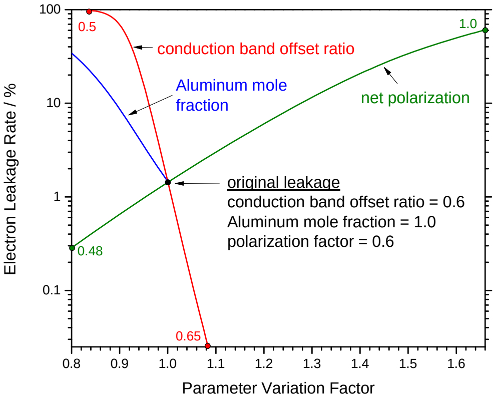

Fig. 3: Sensitivity of the simulated leakage current to EBL parameter variations, using LED structure and leakage measurements from Ref. 25.

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